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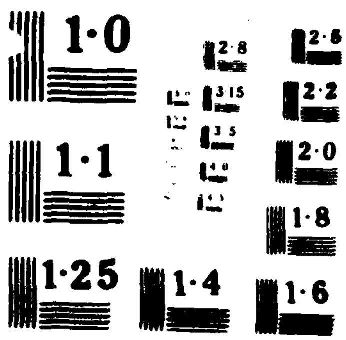
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TRANSVERSE INSTABILITY OF AN ELECTRON BEAM IN BEAM-INDUCED ION CHANNEL

BY K. T. NGUYEN R. F. SCHNEIDER J. R. SMITH H. S. UHM

RESEARCH AND TECHNOLOGY DEPARTMENT

15 SEPTEMBER 1986

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Transverse oscillations of a relativistic electron beam propagating in a beam-induced ion channel has been theoretically investigated and experimentally observed. Good agreement between experimental observations and theoretical calculations strongly suggests that these oscillations may be caused by the ion hose (ion resonance) instability.

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FOREWORD

Transverse oscillations of a relativistic electron beam propagating in a beam-induced ion channel has been theoretically investigated and experimentally observed. Good agreement between experimental observations and theoretical calculations strongly suggests that these oscillations may be caused by the ion hose (ion resonance) instability.

Carl W. Larson

CARL W. LARSON, Head
Radiation Division

We have investigated the transverse oscillations of an electron beam propagating in a beam-induced plasma channel. From the comparison of both theoretical and experimental results, it is strongly suggested that the transverse oscillations are caused by the electrostatic transverse coupling between the electron beam and the ion channel, which is known as the ion hose (ion resonance) instability.[1,2] However, in previous studies,[1,2] the usual assumption was that the charge neutralization fraction f (channel ions to beam electrons line density ratio) was a constant from beam head to tail. In this context, it is necessary to develop a new theoretical model, which can describe some important physical phenomena, for the case where f varies from head to tail and the beam is self-pinched without an external magnetic field.

In this report, we consider an intense relativistic electron beam, with Gaussian profile and radius R, propagating through an initially neutral gas. The axial velocity of the beam is $V\hat{e}_z \simeq c\hat{e}_z$. The beam space charge is partially neutralized by the ions in the plasma channel generated by the beam itself, with the channel electrons assumed to be instantaneously expelled in the absence of external applied axial magnetic field. Secondary ionization is neglected in the low pressure regime considered here. The neutralization fraction, f(t), as a function of time can be approximately given by

$$f(t) = \frac{N_i(t)}{N_b} = \sigma c n_n t = \frac{t}{t_0}, \qquad (1)$$

for $f < 1$. Here N_i and N_b are line densities of ions and beam electrons, respectively, σ is the ionization cross section, n_n is the neutral gas density (~ pressure, P), and $t_0 \equiv (\sigma c n_n)^{-1}$. Strictly speaking, Equation (1) is a crude estimation, since in reality, the beam assumes a trumpet profile, i.e., R is a rapidly changing function of time until the equilibrium condition[3] $f = 1/\gamma^2 + 2T_\perp/\nu mc^2$ is achieved. Here, γ is the beam relativistic factor, $T_\perp$ is the beam transverse temperature, and $\nu = 2.82 \times 10^{-13}\, N_b(\mathrm{cm}^{-1})$ is the well known Budker's parameter. However, this approximation makes the problem analytically tractable, and is actually quite good within the framework of the "rigid" beam and channel treatment considered here.

In the rigid approximation, the beam and ion channel are treated as rigid but flexible rods. The transverse displacements of the beam and channel centroids, D_b and D_i, can be obtained from

$$
\begin{aligned}
N_b \gamma m_e \frac{d^2 D_b}{dt^2} &= F_{bi}(D_b - D_i), \\
N_b m_i \frac{d}{dt} f \frac{dD_i}{dt} &= F_{ib}(D_i - D_b),
\end{aligned}
\tag{2}
$$

for $f < 1$. Here m_i and m_e are the ion and electron rest masses, and $F_{ij}(x)$ is the electrostatic force exerted on column i by column j, with relative centroid displacement distance x. For two columns with Gaussian profiles and equal radii, we can obtain

$$F_{ij}(x) = \frac{2e_i e_j N_i N_j}{x}\left(1 - e^{-x^2/2R^2}\right)$$

$$\simeq e_i e_j N_i N_j \frac{x}{R^2}, \qquad \text{for } x << R. \tag{3}$$

Making use of Equations (1) and (3), Equation (2) can be rewritten as

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right)^2 D_b = \alpha \frac{t}{t_0}(D_i - D_b), \tag{4a}$$

and

$$\frac{1}{t}\frac{\partial}{\partial t} t \frac{\partial D_i}{\partial t} = \eta\alpha(D_b - D_i), \tag{4b}$$

where $\alpha = e^2 N_b/\gamma m_e R^2 \simeq c^2 I_b(kA)/17\gamma R^2$, and $\eta = \gamma m_e/m_i$. Noting that $\eta << 1$, and that z enters Equation (4) only through $\partial/\partial z$, we seek solution to Equation (4) of the form

$$D = \hat{D}(t)\, e^{-ik_z z}, \tag{5}$$

with $|\partial\hat{D}/\partial t| << k_z c$. It is furthermore required that $k_z^2 R^2 \lesssim 1$, which assures the validity of the rigid treatment. Then by substituting Equation (5) into Equation (4a), we obtain

$$\left[-2ik_z c\frac{\partial}{\partial t} - \left(k_z^2 c^2 - \alpha\frac{t}{t_0}\right)\right]\hat{D}_b = \alpha\frac{t}{t_0}\hat{D}_i,$$

which can be integrated to give

$$\hat{D}_b \approx \hat{D}_i + i\,\frac{k_z c}{2}\,e^{-i\delta(t)}\int_{-\infty}^{t} e^{i\delta(t')}\,\hat{D}_i(t')\,dt'. \qquad (6)$$

In Equation (6), $\delta(t)$ is determined by $\delta(t) = (\alpha\, t^2/2t_0 - k_z^2 c^2 t)/2k_z c$. Substituting $\hat{D}_b$ in Equation (6) into Equation (4b) gives

$$\frac{\partial}{\partial t}\left(e^{i\delta(t)}\,\frac{1}{t}\,\frac{\partial}{\partial t}\,t\,\frac{\partial \hat{D}_i}{\partial t}\right) = i\,\frac{n\alpha k_z c}{2}\,e^{i\delta(t)}\,\hat{D}_i. \qquad (7)$$

The full behavior of Equation (7) is complicated and can only be calculated numerically. The detailed results will be presented elsewhere. However, Equation (7) can be approximated to

$$\frac{\partial^3 \hat{D}_i}{\partial t^3} + i\,\delta'\,\frac{\partial^2 \hat{D}_i}{\partial t^2} = i\,\frac{n\alpha k_z c}{2}\,\hat{D}_i, \qquad (8)$$

without loss of important physical contents. Here δ' is defined by $\delta' = (\alpha t/t_0 - k_z^2 c^2)/2k_z c$.

For the region $\delta' \approx 0$, Equation (8) can be solved to give $\hat{D}_i \sim e^{i\omega t}$, where

$$\omega = \frac{1}{2}\,(1 - i\sqrt{3})\,\left(\frac{n\alpha k_z c}{2}\right)^{1/3}. \qquad (9)$$

Away from this region, Equation (8) can be approximated by

$$\frac{\partial^2 \hat{D}_i}{\partial t^2} = \frac{n\alpha k_z c}{2}\,\frac{\hat{D}_i}{\delta'}, \qquad (10)$$

which indicates stable oscillations for $\delta' < 0$, and purely growing for $\delta' > 0$.

From this theoretical analysis, we conclude that, for an electron beam propagating through an initially neutral gas, the ion resonance mode for a given axial wavelength k_z becomes unstable at time $t_d = k_z^2 c^2 t_0/\alpha$, and that growing oscillations given by Equation (9) can be observed only for very low pressure (large t_0) regime. In reality, for $f = t/t_0 \lesssim 1/\gamma^2 + 2T_\perp/\gamma mc^2$, the beam radius R is large and rapidly changing, and thus long wavelength modes such that $k_z^2 c^2/\alpha < 1/\gamma^2 + 2T_\perp/\gamma mc^2$ are stabilized by wall effects and betatron detuning. The unstable mode observed are expected to be the longest axial wavelength that satisfies the condition

$$\frac{k_z^2 c^2}{\alpha} \gtrsim \frac{1}{\gamma^2} + \frac{2T_\perp}{\gamma mc^2}, \tag{11}$$

and the onset time of this instability is

$$t_d = \frac{k_z^2 c^2 t_0}{\alpha} . \tag{12}$$

The experiment is performed with the Transbeam accelerator, which generates a nominal 700 kV, 100 kA, 100 ns pulse into a matched load. The matched electron beam diode consists of a 7.5 cm diameter planar carbon cathode and 13 micron titanium anode foil with a 15 mm anode-cathode gap. In order to obtain a low current, high quality beam, a graphite beam stop with a 2 cm diameter hole on axis is placed immediately downstream of the anode foil. This allows approximately 4 kA of the beam to be injected into the gas-filled drift region. Typical diode current and voltage traces for this configuration along with further details of the accelerator design and operation may be found in Reference 4. Also in Reference 4 we have characterized the beam propagation in the ion focused regime (IFR). The radial profile and root-mean-square (rms) emittance of the beam have been measured with a simple emittance meter and a radiachromic film detector. The beam is characterized by a transverse temperature of 35 keV and a rms radius of about 1 cm.

The experimental setup which has been used to observe transverse oscillations[5] in the ion focusing regime is shown in Figure 1. The drift region is constructed of 15 cm diameter stainless steel tubes with a total length of 1 meter. A passively integrated Rogowski coil is used to measure the net current 30 cm downstream of the diode. A magnetic probe array[6] is placed adjacent to the Rogowski coil. Together these signals will give information about the current centroid displacement from the axis as a function of time. Further details of the experiment may be found in Reference 5. In order to perform open shutter photography, approximately 60 cm of the drift tube can be replaced by a Pyrex tube with a stainless steel screen insert.

The experiment is performed with 10, 20, 30, 40, 80, or 160 mTorr of Argon or Nitrogen as filling gas. In all cases, transverse displacements are detected from the probe array during the beam pulse. In many instances, the instability is so violent that the beam current centroid is displaced a large fraction of the wall radius of the drift tube. In several cases, at the lower pressures, it is possible to identify a frequency associated with the oscillation. The signal at higher pressures is often just a centroid displacement to one side. Delay time from the onset of the current pulse at the probe position to the onset of the instability was also observed in all cases. Figure 2 shows traces of the beam current pulse and the centroid displacement waveform for a low and a high pressure discharges.

In order to relate the experimental observations to the theoretical calculations, we note that the axial wavelength, λ_z, of the perturbation is given by

$$k_z = 2\pi/\lambda_z = \pi n/100 \text{ cm}^{-1}, \; n = 1,2,3, \ldots \tag{13}$$

since the eigenfunctions must vanish at both conducting endplates of the 1 meter long drift tube. Making use of the relevant experimental parameters (I_b = 4 kA, R = 1 cm, γ = 2.4, $T_\perp$ = 35 keV) and Equation (11), we obtain $k_z \gtrsim 0.254$ cm^{-1}, which indicates $\lambda_z \approx 25$ cm. This axial wavelength is evidenced in the open shutter photograph shown in Figure 3, taken with the Pyrex tube in place.

The oscillation frequencies for very low pressure cases can now be found, with λ_z = 25 cm, from Equation (9) to be 17.6 MHz for Argon and 25 MHz for atomic Nitrogen. These values are in good agreement with experimental data at 10 mTorr, which are 17 ± 3 Mhz and 27 ± 1 MHz for Argon and Nitrogen, respectively.[5]

For both Argon and Nitrogen, the characteristic ionization time t_0 is given approximately by 1200/P(mTorr) nanoseconds.[7] Equation (12) can then be used to estimate the delay time for the onset of the instability, which is

$$t_d = \frac{770}{P(\text{mTorr})} \text{ nanoseconds.} \tag{14}$$

As can be seen from Figure 4, Equation (14) well characterizes the behavior of the experimentally determined onset time for Argon (a similar situation occurs for Nitrogen).

In conclusion, ion hose instability of an intense relativistic electron beam propagation in a beam-induced plasma channel has been investigated. Experimental observations agree well with the theoretically calculated values in terms of the axial wavelength, oscillation frequency, and the onset time of the ion hose instability.

This work was supported by the Independent Research Fund at the Naval Surface Weapons Center.

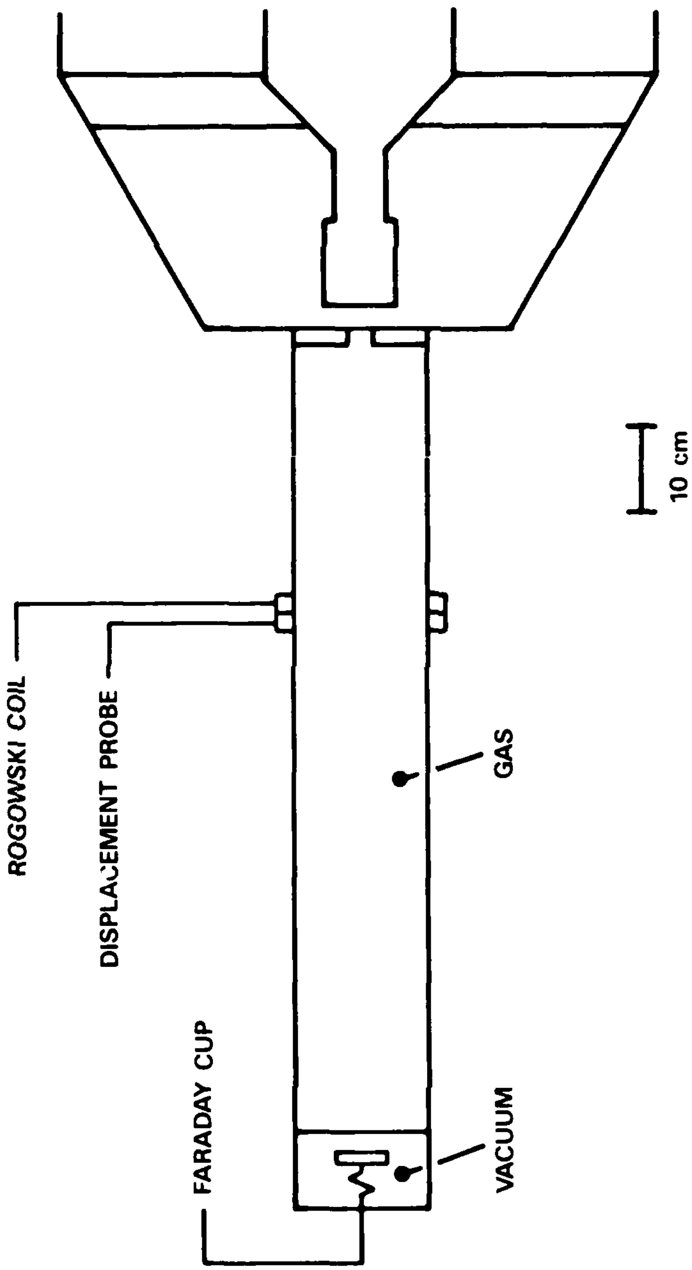
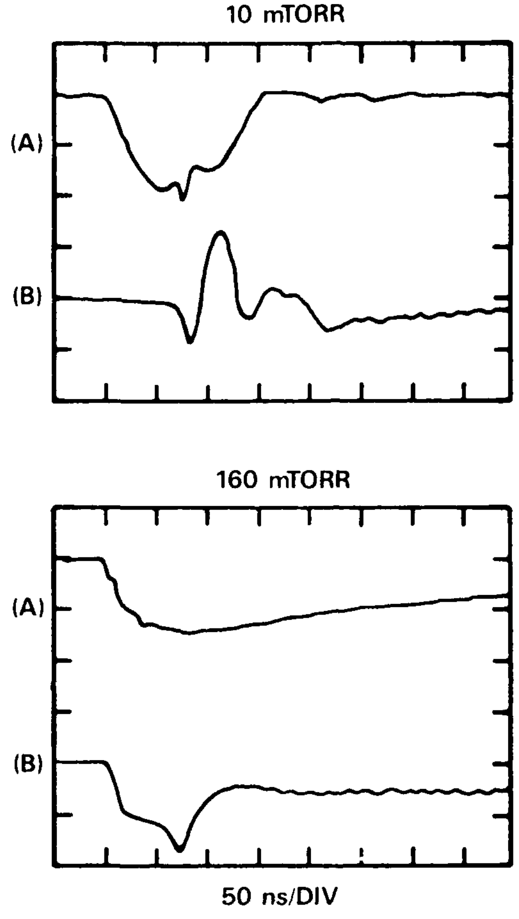
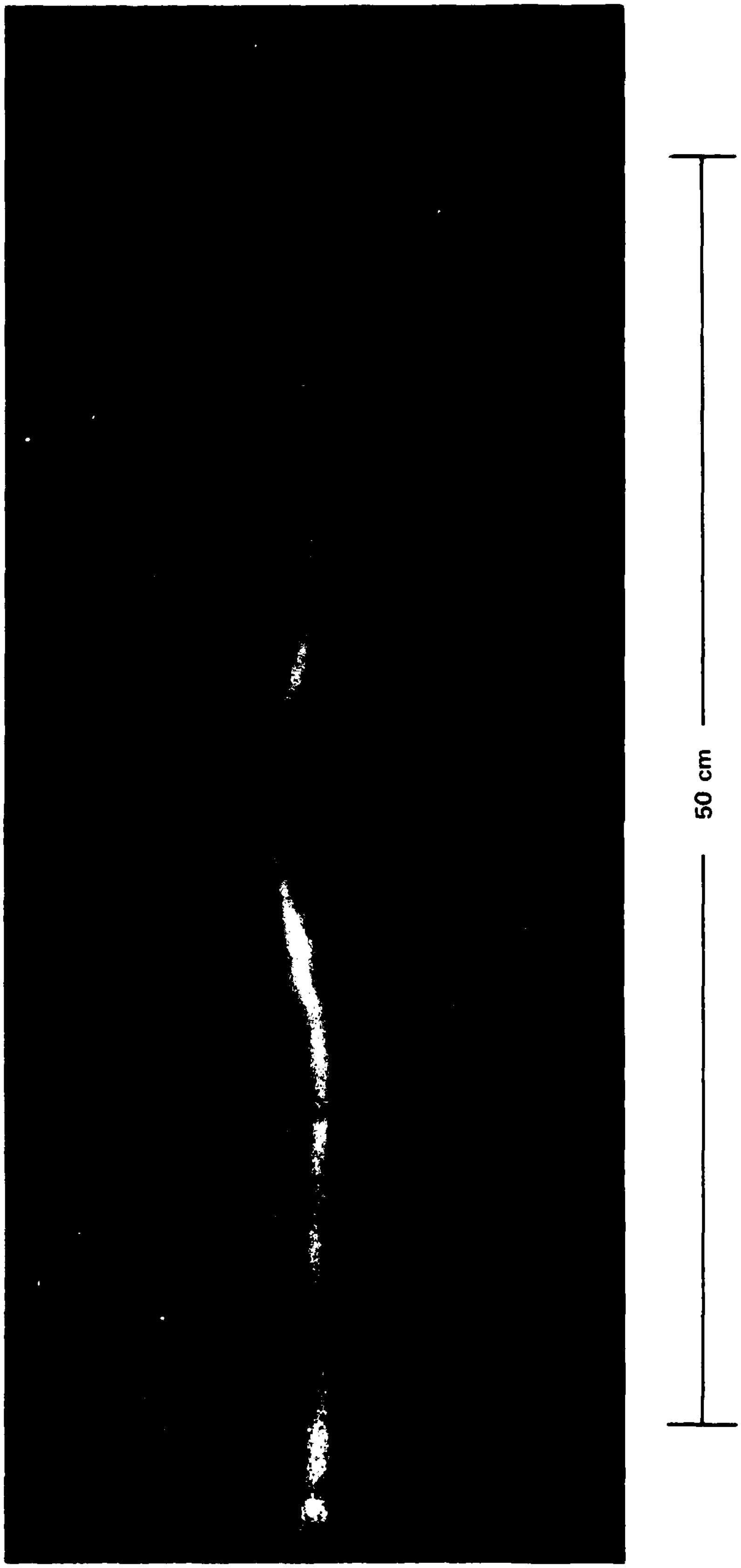


FIGURE 1. EXPERIMENTAL SETUP



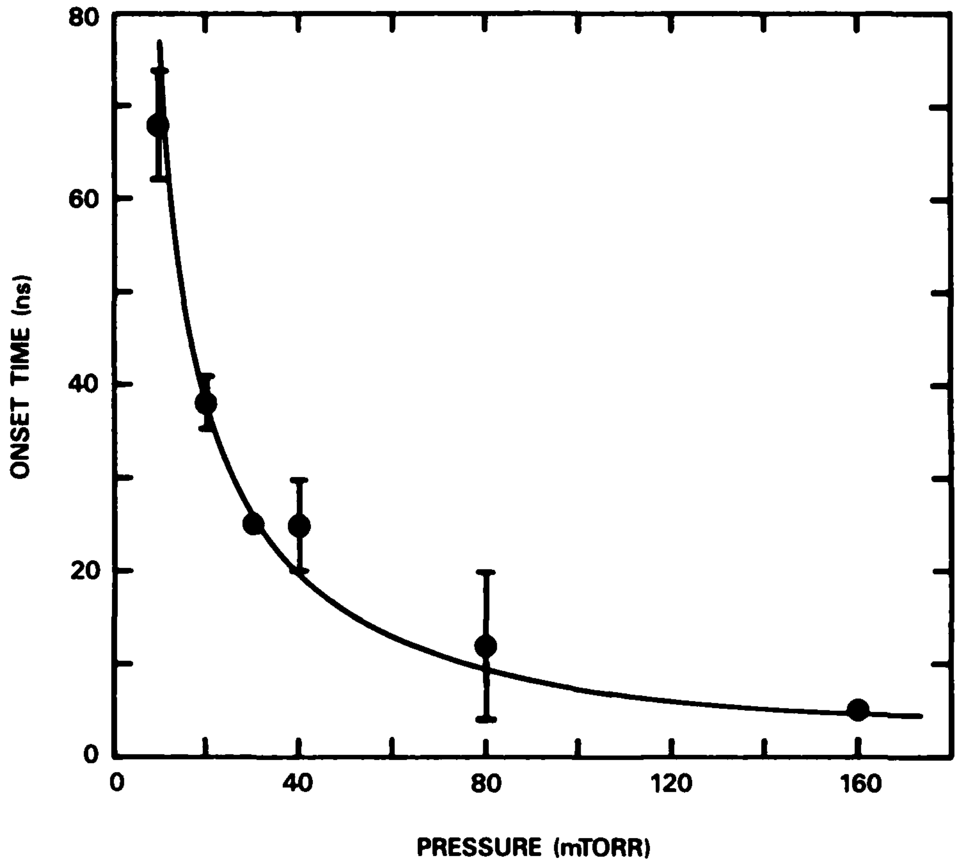
OSCILLOSCOPE TRACES OF THE PASSIVELY INTEGRATED ROGOWSKI COIL AND THE DISPLACEMENT PROBE. THE ROGOWSKI TRACE (A) IS 1.2 kA/DIV. THE DISPLACEMENT PROBE TRACE (B) IS 0.94/I(kA) cm/DIV FOR SMALL DISPLACEMENTS MUCH LESS THAN THE DRIFT TUBE RADIUS.

FIGURE 2. CURRENT AND DISPLACEMENT TRACE



OPEN SHUTTER PHOTOGRAPH OF LIGHT EMITTED DURING PASSAGE OF ELECTRON BEAM THROUGH 40 mTORR OF NITROGEN.

FIGURE 3. OPEN SHUTTER PHOTOGRAPH



PLOT OF THE INSTABILITY ONSET TIME AS A FUNCTION OF PRESSURE FOR ARGON. THE ERROR BARS ABOUT THE EXPERIMENTAL POINTS ARE SAMPLE STANDARD DEVIATIONS. THE SOLID LINE REPRESENTS THE THEORETICAL PREDICTION DERIVED IN THIS PAPER.

FIGURE 4. INSTABILITY ONSET TIME VS PRESSURE

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